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MONSOON AND DICKEY: TWO PHOSPHORUS-RICH BROWN-WATER LAKES WITH LITTLE EVIDENCE OF VERTEBRATE PREDATION PRESSURE ON THE ZOOPLANKTON COMMUNITY

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December 1983

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The existing ability of two sub-arctic brown water lakes (Monsoon and Dickey) to rear juvenile salmonids was determined in order that the proper enhancement technique, either lake fertilization or supplemental fry introduction, could be applied to each system depending on whether the fry rearing capacities were either overtaxed or underutilized.

In general, phosphorus, silicon and carbon (alkalinity) levels were very high for Alaskan lakes, and remained high throughout the summer period however, inorganic nitrogen levels were extremely low. Thus, an increase in the quality of phytoplankton could be achieved by an increase in the N:P ratio through the introduction of a inorganic nitrogen fertilizer. The zooplankton community showed little evidence of existing vertebrate predation pressure i.e., the current fry rearing potential was underutilized. Instead, the zooplankters appeared to be heavily preyed upon by the calanoid *Heterocope septentrionalis*. The cladoceran component of the zooplankton community was extremely weak being typified by a lack of Bosminids and by the presence of *Daphnia longiremus* f. *cephala* and *Daphnia middendorffiana* two large bodied forms able to resist *Heterocope* predation.

The introduction of supplemental fry should reduce the *Heterocope* population resulting in a shift within the zooplankton community towards increased production within the cladoceran component. Finally, to take advantage of the current relatively large body-size of all zooplankters, fish stock introduction should proceed with those species capable of effectively foraging only large zooplankters.

INTRODUCTION

The capacity of fresh water lakes to serve as rearing areas for salmonid fry is linked in successive fashion from the physical and chemical environment, to the production of phytoplankton and, in turn, to the production of zooplankton. Zooplankton, being the basis for rearing fresh water planktivorous fish, are the critical link in the aquatic food chain. As both biomass and energy are transferred up the food chain by successive predatory steps, the predators, in turn, structure the community composition of their prey. As the predation pressure on the zooplankton increases, particular zooplankters are more effectively utilized. Thus, an analysis of the community composition of the standing crop of prey items can define the degree or pre-existing magnitude of the predation process i.e, define either an under or over utilized fry rearing area. In addition, concurrent studies on the nutrient dynamics within both systems will allow us to determine the potential of either system for inclusion into the lake enrichment program.

An expanded lake inventory and assessment project on the upper Copper River drainage was initiated in September of 1981. The purpose of this project was twofold: (1) to identify suitable lake systems with excess rearing potential to be used by fry e.g., sockeye salmon (*O. nerka*) produced at the Gulkana Spring incubation facility, and (2) to identify systems with pre-existing fish stocks that would prove feasible for the enhancement of an overtaxed rearing area via lake enrichment. For example, the potential capacity of the Gulkana Springs facility may be upwards of 90 million eggs, but before expansion can occur, suitable sockeye salmon fry rearing sites must be identified. In addition, several lakes off the Gulkana River have been observed to support remnant populations of sockeye salmon which maybe enhanced by increasing the nutrient supply to the trophogenic zone. Thus, intensive limnological studies were initiated on two such lkes, Monsoon, and Dickey, which were identified earlier as candidates for either supplemental fry introduction or for lake enrichment.

Description of Study Area

Dickey Lake is located at latitude 60°55'3", longitude 146°05'9" on the middle fork of Gulkana River (Figure 1) at an elevation of approximately 884 m. The surface area of the lake is $3.13 \times 10^{+6}$ m^2 (774 acres) while the watershed encompasses $11.9 \times 10^{+6}$ m^2 (2,943 acres). The maximum depth of Dickey lake is 25 m with a mean depth of 15 m, and a volume $43.7 \times 10^{+6}$ m^3 (Figure 2). There is one major inlet located at the south end of the lake which drains a tundra bog.

Monsoon Lake is located at latitude 62°49', longitude 146°38' on the west fork of the Gulkana River (Figure 1) at an elevation of approximately 913 m. The surface area of the lake is $0.31 \times 10^{+6}$ m^2 (77 acres) with a watershed area of $11.9 \times 10^{+6}$ m^2 (2,938 acres). The maximum depth of Monsoon Lake is 19 m with a mean depth of 8 m, and a total volume of $2.5 \times 10^{+6}$ m^3 (Figure 3). There are two major inlets, one at the northern end of the lake and the other entering the middle of the lake on the eastern shore.

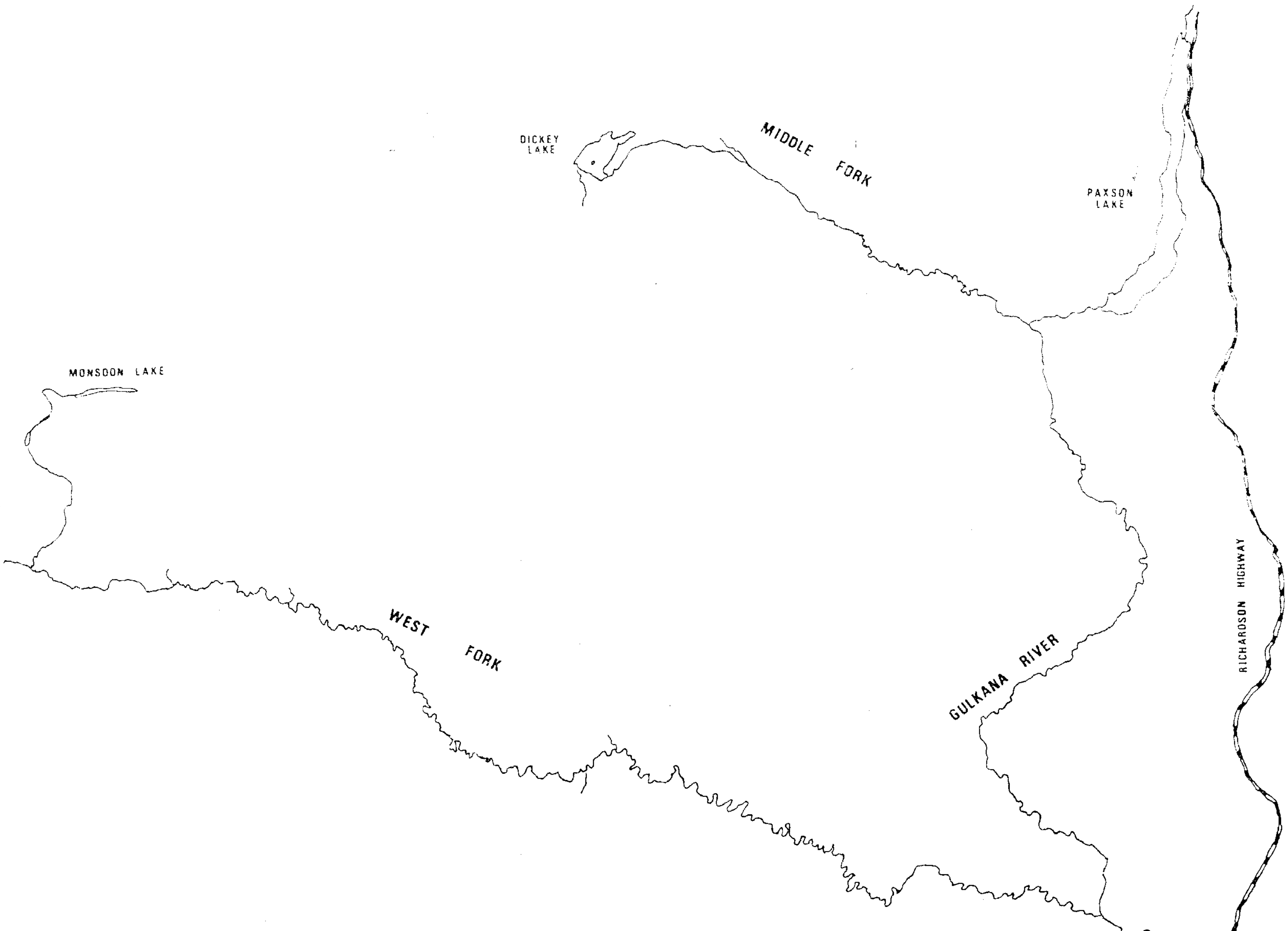


Figure 1. Area map of the Gulkana River showing location of Monsoon and Dickey Lakes.

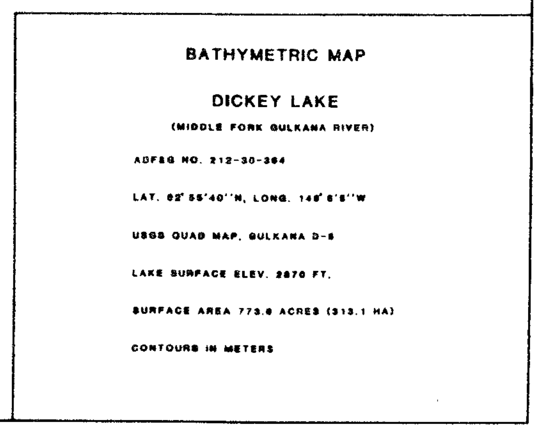


Figure 2. Bathymetric map of Dickey Lake showing the location of the limnological sampling site (✱).

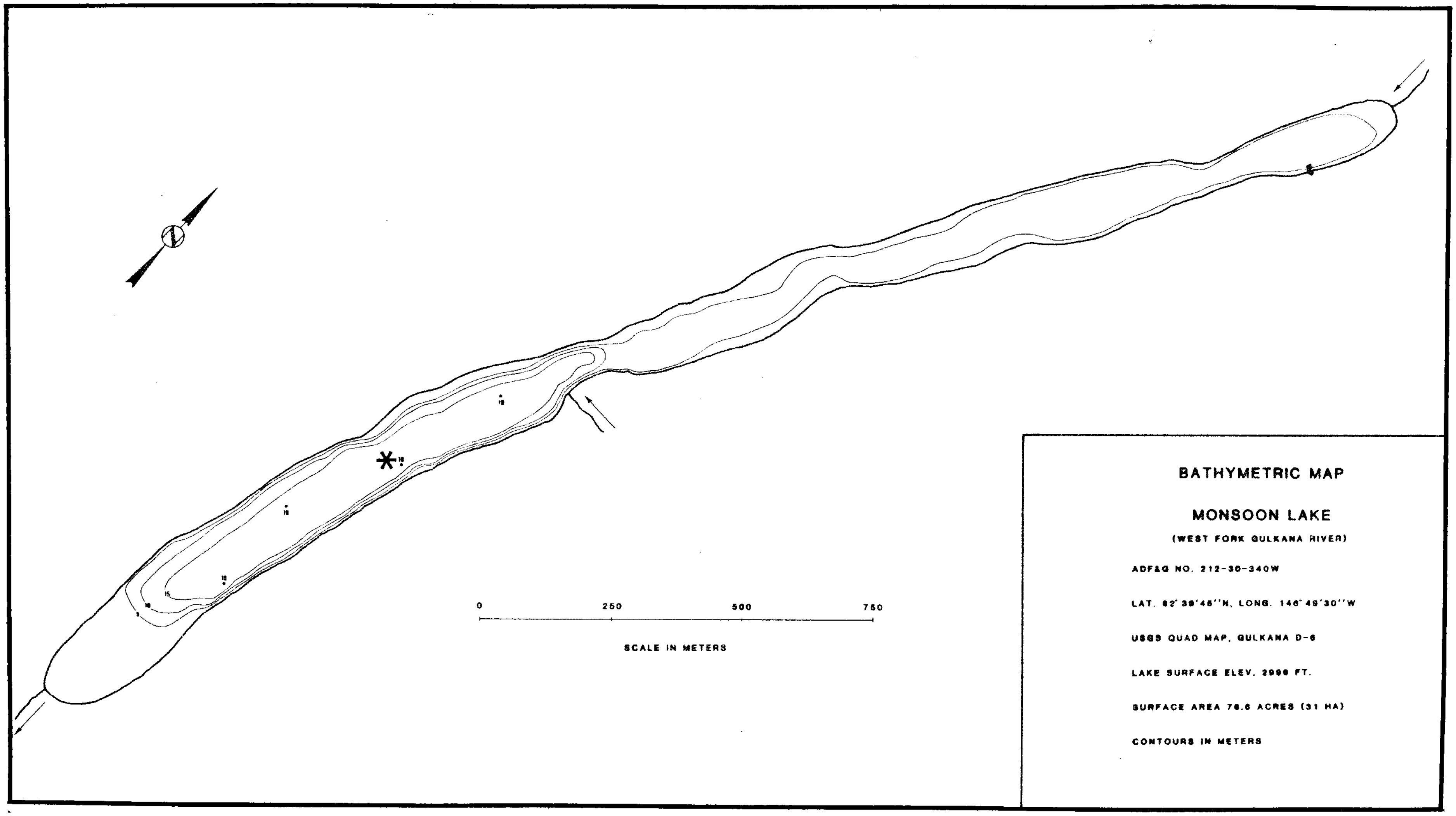


Figure 3. Bathymetric map of Monsoon Lake showing the location of the limnological sampling site (✱).

METHODS

Transportation to and from both lakes was provided by float/ski equipped aircraft. Limnological samples were collected from the aircraft floats during ice-free periods after mooring to permanent sampling stations. The frequencey of sampling was designed to characterize the lake at three intervals during the ice-free period i.e., spring, summer and late fall as well as twice during the winter period. The lake was sampled for algal nutrients (nitrogen, phosphorus, silicon and carbon) as well as other water quality parameters (see Alaska Department of Fish and Game, Lake Fertilization Guidelines) from both the epilimnetic (1 m) and mid-hypolimnetic Water samples from multiple (4) casts with a non-metalic Van Dorn sampler were pooled, stored in 8-10 liter transluscent carboys, cooled, and immediately transported in light-proof containers to Glennallen and/or Cordova for filtering and preservation. Subsequent filtered and unfiltered water samples were stored either refrigerated or frozen in acid-cleaned (10% HCl), pre-rinsed polybottles. The pre-processed water samples were then sent to the Soldotna limnology laboratory for analysis.

All chemical and biological samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology manual (Koenings et al., 1980). In general, filterable reactive phosphorus (FRP) was analyzed by the molybdate blue-ascorbic acid method of Murphy and Riley (1962) as modified by Eisenreich et al. (1975). Total phosphorus was determined by the FRP procedure after persulfate digestion. Nitrate and nitrite were determined as nitrite following Stainton et al. (1977) after cadmium reduction of nitrate. Ammonium analysis followed Stainton et al. (1977) using the phenolhypochlorite methodology while silica analysis followed the procedure of Strickland and Parsons (1972). Alkalinity was determined by acid titration (0.02 N H_2SO_4) to pH 4.5 using a Corning model 399A specific ion meter.

Primary production (algal standing crop) was estimated by chlorophyll *a* (chl *a*) analysis after the fluorometric procedure of Strickland and Parsons (1972). We used the low strength acid addition recommended by Reimann (1978) to estimate phaeophytin. Water samples (1-2 liters) were filtered through 4.25 cm Whatman GF/F filters to which 1 to 2 mls of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in individual plexislides for later analysis.

Zooplankton were collected from duplicate bottom to surface vertical tows using either a 0.5 m or 0.2 m diameter (depending upon season), 153 μ mesh conical zooplankton net. The net was pulled at constant 1 m/second, and washed well before removing and then preserving the organisms in 10% neutralized sugar-formalin (Haney and Hall 1973).

Identification within the genus *Daphnia* followed Brooks (1957), of the genus *Bosmina* after Pennak (1978), and of the copepods after Wilson and Yeatman (1959) and/or Harding and Smith (1974). Enumeration consisted of counting triplicate 1 ml subsamples taken with a Hansen-Stempel pipette in a 1 ml Sedgewick-Rafter cell. Size (length) of individual zooplankton were obtained by measuring individuals along a transect in each of the 1 ml subsamples used in identification and enumeration. Zooplankton were measured to the nearest 0.01 mm as described in Edmondson and Winberg (1971).

Bottom profiles were recorded with a Si-Tex model 256 recording fathometer along several lake transects and from these depth recordings bathymetric maps were developed. Using each map, the area of component depth strata were determined with a polar planimeter with lake volume (V) being computed by summation of successive strata after Hutchinson (1957):

$$\text{Lake Volume} = \sum_{i-1}^{n} \frac{h}{3} \left(A_1 + A_2 + \sqrt{A_1 A_2}\right)$$

Where: $\sum_{i-1}^{n}$ = sum of strata volumes i through n

A_1 = surface area of upper depth strata (m^2)

A_2 = surface area of lower depth strata (m^2)

h = distance between A_1 and A_2 (m)

Lake mean depth ($\bar{z}$) was calculated as:

$$\bar{z} = V/A_L$$

Where: A_L = lake surface area (m)

v = lake volume ($\cdot 10^6 m^3$)

The collection of physical data included the measurement of within lake temperature and light penetration profiles. Lake temperature profiles were measured using a YSI model 51 meter with recordings taken at 1 m increments from the surface to the lake bottom. The algal light compensation point was defined as the depth at which 1% of the subsurface light [photosynthetically available radiation (400-700 mm)] penetrated, and was measured using a Protomatic submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. Using these data, the natural logarithm of light intensity was plotted against depth, and the slope of this line was used to calculate the light extinction coefficient by date. In addition, water transparency was estimated using a 20-cm Secchi disk.

Finally, in both the Tables and Figures we have used the designation of either mg L^{-1} or $\mu g\ L^{-1}$ to report concentration data. However, in the body of the report we have used either parts per million (ppm) in lieu of mg L^{-1} and parts per billion (ppb) in lieu of $\mu g\ L^{-1}$. We have made this conversion in order to reduce the handling time of the report by our support staff.

RESULTS

Dickey Lake

Physical Features

The euphotic zone (defined by penetration of 1% of sub-surface light) ranged from 3.3 m in June to 5.5 m by late September, and averaged 4.4 m (Table 1). Thus, the euphotic zone occupied from 22% to 36% of the total lake volume, and averaged 29% over the summer season. In June, the epilimnion (as defined by the depth of the thermocline) extended to 8 m, and in August had decreased slightly in depth to 7 m. Thus, the wind mixed upper strata occupied from 44% to 50% of the total lake volume. A comparison of the depth of the euphotic zone to that of the epilimnion is limited to June and August because of isothermal conditions found before June and during the September sampling period. However, in June the euphotic zone occupied approximately 50% of the epilimnion which increased in August to encompass nearly three-fourths of the epilimnetic volume. Finally, the Secchi disk depth represented an average, over the ice-free season, of nearly 85% of the depth of the euphotic zone.

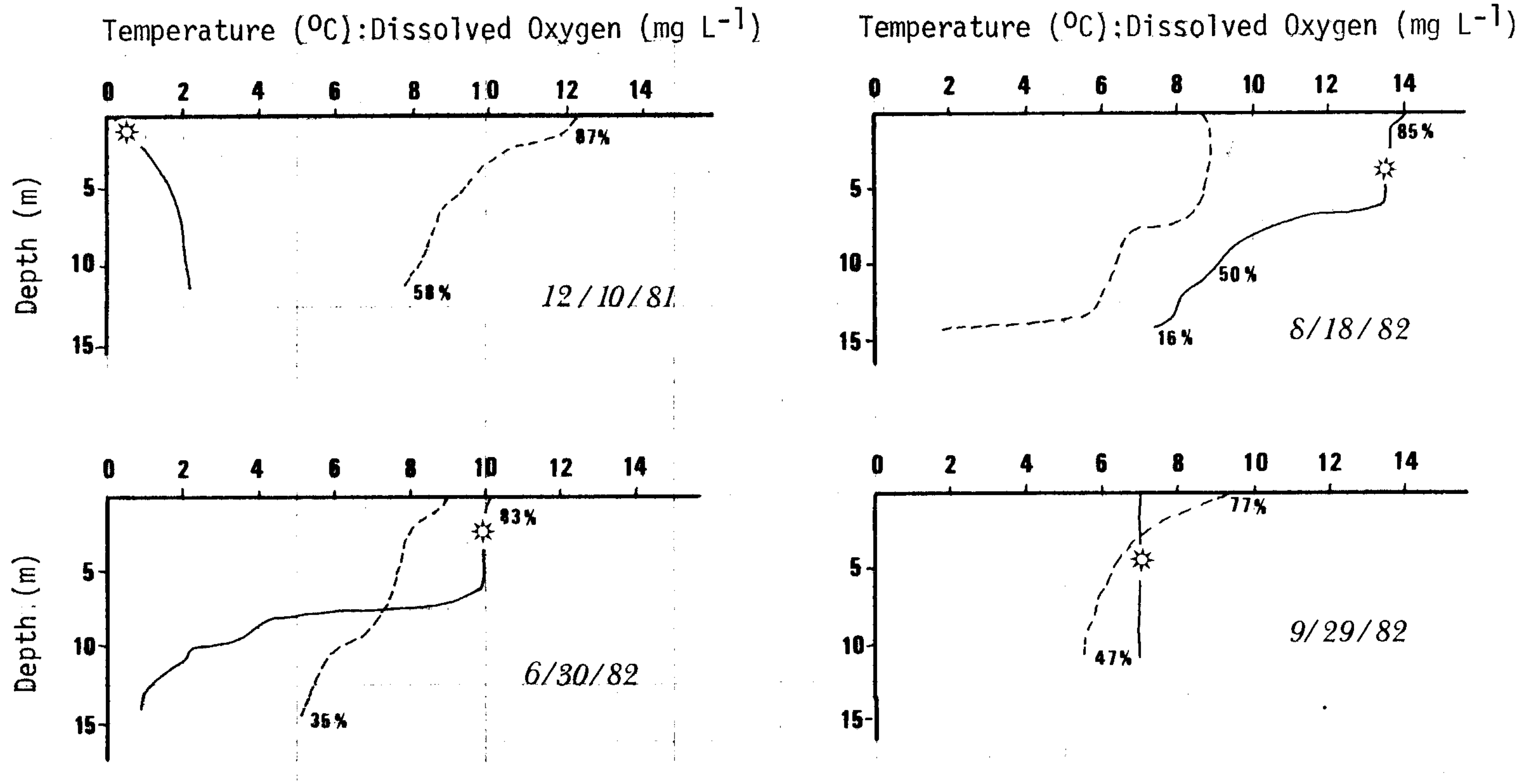
During June and August, maximum epilimnetic temperatures were 10°C and 14°C respectively (Table 1). In addition, the temperature profiles suggest that a large amount of hypolimnetic heating occurred especially between the 30 June and 18 August sampling dates (Figure 4). In June, the hypolimnetic stratum was at approximately 1°C which increased to >8°C by the middle of August. Since the maximum density of freshwater is 4°C and the lake was thermally stratified this change in temperature indicated that either the thermal structure had dissipated and reformed between the two dates or that the thermal structure of the water column was significantly influenced by the location of the sampling station immediately adjacent to the shore of the lake (Figure 4). The dissolved oxygen profiles support the later observation since the amount of dissolved oxygen in the hypolimnion was almost constant (approximately 6 ppm) from June through the end of September; whereas, the temperature profiles were completely different. Thus, lake mixing probably did not occur, and basin heating (thawing) accounted for the change in the temperature profiles from June to August.

Dissolved Gases

The dissolved oxygen concentrations (D.O.) exceeded 10 ppm only during the mid-winter surface sample when levels in excess of 12 ppm were observed (Table 1). However, even during this later date the percent saturation of oxygen within the water column was <90%. In fact, the surface strata contained oxygen levels at less than 90% saturation (77%-87%) on all dates sampled (Figure 4). In addition, hypolimnetic oxygen levels never exceeded 60% of saturation (47% to 58%); however, dissolved oxygen levels were at or above 6 ppm on all dates sampled. The lowest D.O. readings were observed immediately adjacent to the lake bottom near the littoral zone where levels <2 ppm were found which represented from 17% to 35% saturation.

Table 1. The surface temperature, dissolved oxygen (D.O.) content, depth of the euphotic zone, Secchi disk depth, and the magnitude of snow and ice cover for Dickey Lake.

Date	Surface temperature (°C)	Surface D.O. (mg L^{-1})	Secchi disk (m)	Euphotic zone (m)	Snow depth (cm)	Ice depth (cm)
12/10/81	0.2	12.2	2.5	1.5	20	38
03/15/82	0.0	12.8	1.5	5 cm	25	95
06/30/82	10.0	9.0	2.0	3.3	--	--
08/18/82	14.0	8.4	3.3	4.5	--	--
09/29/82	7.1	9.4	4.0	5.5	--	--



Key: —— Temperature. ---- Dissolved Oxygen. ☼ Depth of the euphotic zone.

Figure 4. Temperature and dissolved oxygen profiles (with percent oxygen saturation) for Dickey Lake showing the changing depth of the epilimnion and the euphotic zone.

Table 2. General water quality parameters from Dickey Lake, 1981-82.

Parameter	Seasonal mean value ± S.D. (n=5) 1 m	8 m
Conductivity (μmhos cm^{-1} @ 25°C)	79 ± 10	78 ± 9
pH	7.44 ± 0.19	7.39 ± 0.14
Alkalinity (mg L^{-1} as $CaCO_3$)	41 ± 6	41 ± 4
Calcium (mg L^{-1})	11 ± 2	11 ± 2
Magnesium (mg L^{-1})	3 ± 1	3 ± 1

General Water Quality Parameters

As the deeper sampling depth (8 m) was never within the hypolimnion, the samples represent the water quality at the top (1 m) and the bottom (8 m) of the epilimnion. As such, the parameters (Table 2) are markedly similar and show little demonstratable difference between the upper and lower layers of the epilimnion. In addition, the conductivity values ($\sim$79 μ mhos) and alkalinity levels are moderately high for Alaskan lakes especially in comparison to the more coastal systems. We found that the levels of calcium (11 ppm) and magnesium (3 ppm) were again high; and, in addition, that the pH was slightly higher than neutral whereas for many Alaskan lakes the norm generally lies on the slightly acidic side of neutral.

Nutrient Cycles

Reactive silicon levels within the epilimnion were high both in comparison to other Alaskan lakes and on an in lake seasonal basis (Table 3). Concentrations ranged from just below 4,000 ppb to slightly more than 2,500 ppb. However, the similarity within the seasonal concentration pattern suggested a lack of utilization of reactive silicon by diatoms during the ice-free period. That is, there was a trend for the lower strata to retain similar amounts of silicon in the reactive state when compared to the upper strata even during periods when the lake was thermally stratified, i.e., June and August.

In contrast, the seasonal change of inorganic nitrogen levels demonstrates the pattern of nutrient utilization by the phytoplankton. During the ice covered period (from December to March) nitrogen was liberated by microbial decomposition reactions; and, by the further process of nitrification, was metabalized into nitrate. Thus, the concentration of nitrate increased from 44 ppb in December to 80 ppb by the middle of March. After ice-out, algal production quickly reduced the amount of nitrate (and ammonium) to barely detectable levels by the end of June. This condition persisted for the period when a defined epilimnion was present (August); however, by the end of September when the lake became isothermal the epilimnion was resupplied with nitrate through mixing with the hypolimnetic stratum.

The pattern of epilimnetic nutrient utilization found for inorganic nitrogen was mirrored in the seasonal pattern of reactive (inorganic) phosphorus concentrations (Table 3). Again, during the ice-over period, reactive phosphorus accumulated in the water column due to mineralization reactions of the bacteria. However, once the lake was ice-free and the epilimnion formed (by the end of June), reactive phosphorus levels decreased from approximately 33 ppb to 12 ppb, a change of 21 ppb which was accounted for in a 27 ppb increase in particulate (algal) phosphorus. Thereafter, reactive phosphorus levels showed a further reduction into August, but by September levels returned to levels greater than 20 ppb during mixing with hypolimnetic water. Thus, it is apparent from the concentration profiles of each of the primary nutrients (except inorganic carbon levels) that the amounts of reactive silicon, ammonium, nitrate + nitrite, and reactive phosphorus were lower in the upper part of the

Table 3. Nutrient concentrations and algal pigments found within the upper and lower portions of the epilimnion (1 m and 8 m) within Dickey Lake, 1981-82.

		Date				
	Depth	12/10/81	3/15/82	6/30/82*	8/18/82	9/29/82
Total Phosphorus ($\mu g\ L^{-1}$ as P)	1 m	30.9	36.1	45.0	27.8	36.2
	8 m	30.1	33.8	33.2	24.4	36.0
Total Filterable Phosphorus ($\mu g\ L^{-1}$)	1 m	34.6	36.4	17.8	16.7	29.9
	8 m	31.7	35.6	21.2	22.2	31.3
Filterable Reactive Phosphorus ($\mu g\ L^{-1}$)	1 m	24.3	32.8	12.3	9.8	21.3
	8 m	22.0	31.6	16.5	16.4	23.7
Nitrate + Nitrite ($\mu g\ L^{-1}$ as N)	1 m	44	78	$<$0.5	$<$0.5	53
	8 m	44	83	5	6	57
Ammonium ($\mu g\ L^{-1}$ as N)	1 m	16	8	2	2	4
	8 m	3	3	3	5	4
Reactive Silicon ($\mu g\ L^{-1}$ as Si)	1 m	3744	3944	2598	2542	2804
	8 m	3244	3649	3118	2600	2796
Iron ($\mu g\ L^{-1}$ as Fe)	1 m	39	24	126	61	42
	8 m	40	29	154	53	59
Algal Pigments:						
Chlorophyll *a* ($\mu g\ L^{-1}$)	1 m	0.92	0.74	8.13	5.18	2.59
Phaeopytin ($\mu g\ L^{-1}$)	1 m	0.20	0.19	$<$U.D.	0.29	0.42

*1 m and 11 m

epilimnion when compared to the values found for the lower portion of the epilimnion (i.e., the top of the hypolimnion).

Finally, total phosphorus concentrations were, like the reactive phosphorus levels, extremely high compared to any lakes studied thus far in Alaska. Total phosphorus ranges from 24 ppb to 45 ppb and as such represented 450% of the permissible phosphorus loading rate for oligotrophic lake systems (Vollenweider 1976).

Algal Biomass

The concentration of chlorophyll a (chl a) as well as its degradation product, phaeophytin, was measured in the surface strata of the lake (Table 3). Chl a levels were low during the ice-over period at 0.92 ppb and 0.74 ppb during December and March respectively. In addition, there was a relatively high percentage of inactive phaeophytin. During the ice-free period, the level of chl a rapidly peaked at 8.3 ppb by the end of June with little, if any, inactive pigment. As the season progressed, the amount of chl a slowly declined to 5.18 ppb during August and to 2.59 ppb by late September. In addition, the proportion of inactive pigment increased from August to the end of September indicating a decrease in algal quality.

Zooplankton

The zooplankton community of Dickey Lake consisted of five major species of macro-zooplankton including two cladocerans *Bosmina longirostris* and *Daphnia longiremis* (with a small proportion of *Daphnia middendorffiana*) and three copepods *Cyclops columbianus, Diatomus pribilofensis* and *Heterocope septentrionalis* (Table 4). In addition to the macro-zooplankton, three forms of rotifers were found namely; *Kellicottia longispina, Conochiloides* sp. and *Conochilus* sp.

In addition to the individual species of macro-zooplankton, numerical density and seasonal timing are also important factors in the availability of the zooplankters to foraging fry. The cladoceran population was very weak in Dickey Lake throughout the year (rare to 6,228 organism/m^2) except for the end of September when *Daphnia* numbers increased dramatically to 98,726 organisms/m^2. Thus, the filter feeding herbivorous forms of macro-zooplankton showed extremely low population densities throughout most of the sampling dates.

In contrast, the numerical density of the herbivorous rotifers was extremely high forming a significant proportion of the zooplankton community throughout the sampling period. Rotifer density ranged from a low of 33,917 organisms/m^2 ember to a high of 975,308 organisms/m^2 in August.

Numerically, the most important group of macro-zooplankton was the copepods which ranged in density from a low of 9,554 organisms/m^2 in March to a high of 903,081 organisms/m^2 in June. The dominant copepod was the omnivore *Cyclops columbianus*, which was followed in density by the

Table 4. Numerical composition of the zooplankton community at Dickey Lake, 1981-82.

Organism	Number/m^2 Date 12/10/81	3/15/82	6/30/82	8/18/82	9/29/82
Cladocera					
Bosmina longirostris	Rare	0	Rare	239	Rare
Daphnia longiremus forma *cephala*	797	0	Rare	6,228**	98,726
Copepoda					
Cyclops columbianus	57,882	9,554	851,375	287,818	204,458
Diaptomus pribilofensis	5,016	0	45,912*	12,340	7,962
Heterocope septentrionalis	0	0	5,794	1,433	Rare
Rotifera					
Kellicottia longispina	108,519	208,997	322,720	39,809	23,885
Conochiloides sp.	17,277	2,388	111,436	935,509	10,032
Other	23,965	2,030	26,744	0	0

*Immature calanoids, probably *Diaptomus*.
****Daphnia middendorffiana* (rare).

Table 5. Mean body-size [mm ± 1 standard deviation (S.D.)] and sample size (n) of the macro-zooplankton from Dickey Lake, 1981-82.

Taxa	12/10/81 n	12/10/81 X ± S.D.	3/15/82 n	3/15/82 X ± S.D.	6/30/82 n	6/30/82 X ± S.D.	8/18/82 n	8/18/82 X ± S.D.	9/29/82 n	9/29/82 X ± S.D.
Copepoda										
Cyclops	30	0.97±.21	30	0.80±.08	30	0.73±.18	30	0.88±.08	20	0.87±.25
Diaptomus	20	1.42±.06	--	-- --	10	0.65±.08*	20	1.38±.08	20	1.35±.06
Heterocope	--	-- --	--	-- --	7	1.96±.16	7	2.86±.04	3	2.92±.03
Cladocera										
Daphnia	30	0.89±.19	--	-- --	2	0.95±.10	20	1.00±.25**	20	0.98±.21
Bosmina	2	0.67±.04	--	-- --	3	0.57±.01	8	0.53±.11	6	0.59±.08

*Immature calanoid copepod, probably *Diaptomus*.
****Daphnia middendorffiana* (1.85±.28) present in August.

herbivorous calanoid *Diaptomus pribilofensis*, and then by the voracious invertebrate predator *Heterocope septentrionalis*.

A further feature of the macro-zooplankton community of considerable importance to feeding fry is the body-size of the individual zooplankters (Table 5). Of the cladocerans, *Daphnia longiremus* had the largest body-size ranging from 0.89 mm to 1.00 mm, while the body-size of *Bosmina longirostris* ranged from 0.53 mm to 0.67 mm. In addition, the body-size of *Daphnia middendorffiana* was found to reach 1.85 mm, but its representation within the zooplankton community was very weak. Within the copepods, the largest body-size was found for *Heterocope septentrionalis* which ranged in body-size from 1.96 mm to 2.92 mm. Following *Heterocope* in length was *Diaptomus pribilofensis* which had a body-size ranging from 0.65 (immature) to 1.42 mm, and finally by *Cyclops columbianus* which ranged in body-size between 0.73 mm and 0.97 mm.

Resident Fish

Adult sockeye salmon were observed in Dickey Lake during the June sampling period, i.e., run timing is early with adult sockeye salmon appearing in the lake shortly after break-up, and being spawned out by mid-August (Roberson, personal communication). Peak escapement estimates, as determined from aerial surveys, for the past three years were extremely low equalling 250 in 1980, 20 in 1981, and 410 in 1982. Other fish species which were found to occur were lake trout (*Salvelinus namaycush*), whitefish (*Coregonus clupeaformis*), and Arctic grayling (*Thymallus arcticus*).

Monsoon Lake

Physical Features

The euphotic zone (defined by the penetration of 1% of sub-surface light) ranged from 3.5 m in June to 6.0 m in late September (Table 6), and averaged 4.7 m. Thus, the euphotic zone ranged from 36% to 58% of the total lake volume and averaged nearly 50% over the summer season. Like the depth of the euphotic zone, the depth of the epilimnion varied between sampling dates. For example, in June, the epilimnion extended to 4 m, but by August had deepened to 9 m. Thus, the epilimnion represented from 39% to 77% of the total lake volume. A comparison of the euphotic volume to the epilimnetic volume is limited to two dates (June and August) because of ice-covered or isothermal conditions before and after the mid-period sampling dates respectively. In June, the euphotic zone occupied over 90% of the epilimnion, but, by August (because of the deepening thermocline), the euphotic zone represented 75% of the epilimnion. Finally, the Secchi disk depth averaged 3.8 m during the ice-free period compared to an average euphotic zone depth of 4.7 m. Thus, the Secchi disk depth represented 81% of the depth of the euphotic zone.

The maximum surface temperature (14.5°C) was recorded in June followed by generally lower temperatures in August (13.5°C), and in September (6.8°C) (Table 6). During the winter period, the surface temperature (just below

Table 6. The surface temperature, dissolved oxygen (D.O.) content, depth of the euphotic zone, Secchi disk depth, and the magnitude of the snow and ice cover for Monsoon Lake.

Date	Surface temperature (°C)	Surface D.O. (mg/l)	Secchi disk (m)	Euphotic zone (m)	Snow depth (cm)	Ice depth (cm)
12/10/81	0.5	9.3	3	5 cm	25	50
03/13/82	0.0	8.0	2.5	5 cm	25	70
05/05/82[1]	0.1	8.7	--	--	40	100
06/27/82	14.5	12	1	3.5	--	--
08/18/82	13.5	9	4.5	4.5	--	--
09/29/82	6.8	10	6	6.0	--	--

[1]This sample date for temperature and D.O. data only.

the ice) was lowered to 1°C, but the temperature increased with depth reaching 4°C near the lake bottom (Figure 5). During May, a shallow station was sampled for temperature (and for dissolved oxygen) which showed a warming of the deeper water close to the lake bottom. However, like the profile found for December, most of the water column was less than 4°C. This cooling of the pelagic water column to below 4°C could be caused by deep permafrost which surrounds the lake combined with extreme heat loss during the previous fall overturn period. By the end of June, a stable thermal structure had developed separating the lake into two distinct water masses. These distinct layers persisted into mid-August with the epilimnion deepening from <4 m to over 9 m in depth. However, by the end of September, the lake had cooled to an isothermal 6.8° and was presumably mixing from top to bottom.

Dissolved Gases

The dissolved oxygen content of the surface stratum was consistantly greater than 8 ppm, but never exceeded 12 ppm (Table 6). In addition, the percent oxygen saturation within the surface stratum ranged from 65% under the ice in December to 115% during the latter part of June (Figure 5). During August and September, the surface of the lake was only 86%-84% saturated, respectively. Below the surface, the concentration of dissolved oxygen dropped as did the percent saturation. For example, within the hypolimnion, oxygen levels sagged to approximately 6 ppm and (except for June) were ≤57% saturated. Concentrations of oxygen continued to decrease near the bottom to levels at or below 3 ppm (between 18% and 20% of saturation) during December, August and September. In June, the entire dissolved oxygen profile was consistently above 8 ppm (or a low of 63% saturation) even within the bottom strata. Overall, oxygen levels were only critically low within the 15 m to 19 m layer which represented <3% of the total lake volume.

Finally, the dissolved oxygen profile found during August revealed an oxygen pulse at the top of the thermocline at 9-10 meters. The cause of this anomally (as we will discuss later) was a 'bloom' of diatoms located on the top of the thermocline.

General Water Quality Parameters

Conductivity values were relatively high (102 μ mhos cm^{-1}) for Alaska lake systems, and showed a fairly uniform seasonal pattern within both the 1 m depth and the deeper 12 m stratum (Table 7). The lower depth sampled was representative of the hypolimnetic layer except for the August sampling period when the epilimnion had deepened to the point of influencing the 12 m depth. Alkalinity levels were high within both strata at slightly less than 60 mg L^{-1} which corresponded with high calcium (15 ppm to 16 ppm) and magnesium (3 ppm to 4 ppm) levels. Finally, the pH levels within the lake were slightly greater than neutral (approximately 7.5) and showed little variation throughout the sampling period.

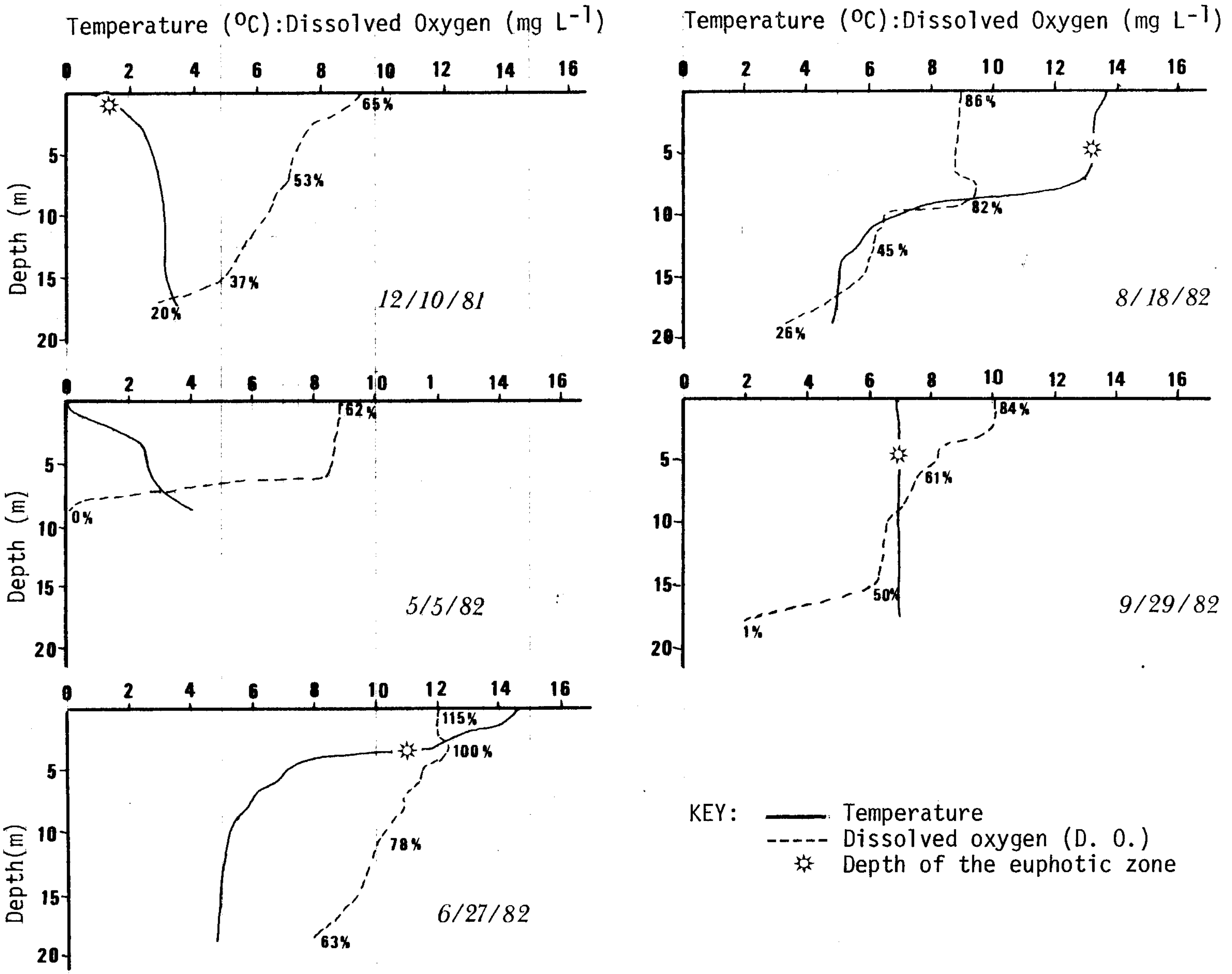


Figure 5. Temperature and dissolved oxygen profiles (with percent oxygen saturation) for Monsoon Lake showing the changing depth of the epilimnion and of the euphotic zone. Note: On 5/5/82, Station 2 was sampled for temperature and dissolved oxygen only.

Table 7. General water quality parameters from Monsoon Lake, 1981-82.

Parameter	Seasonal mean value ± S. D. 1 m	Seasonal mean value ± S. D. 12 m
Conductivity (μmhos cm^{-1} @ 25°C)	102 ± 12	103 ± 9
pH	7.59 ± 0.18	7.51 ± 0.21
Alkalinity (mg L^{-1} as $CaCO_3$)	57 ± 8	58 ± 8
Calcium (mg L^{-1})	15 ± 3	16 ± 2
Magnesium (mg L^{-1})	4 ± 1	3 ± 1

Nutrient Cycles

Reactive silicon levels within Monsoon Lake were relatively high within both the epilimnetic and hypolimnetic strata (Table 8). During the winter, reactive silicon levels were generally greater than 5,500 ppb; however, soon after ice-out, levels of reactive silicon dropped to <4,500 ppb during June. By the end of September, silicon levels had continued to decline, reaching levels of slightly greater than 3,500 ppb. In August there was a a considerable difference in silicon concentrations between the 1 m (4,351 ppb) and 12 m (855 ppb) depths. However, in general, very little seasonal change in silicon levels was observed within the surface strata compared to the hypolimnetic concentration, even during June and August when the lake was thermally stratified.

In contrast to the pattern observed in silicon concentrations, inorganic nitrogen levels (especially nitrate + nitrite) showed a considerable decrease during the ice-free period (Table 8). Ammonium levels during December reached an inlake seasonal high but were extremely low. Thereafter, the ammonium concentration fell even lower, approaching the detection limit of the analysis method, by late September. In addition, very little difference was observed in ammonium levels between the epilimnetic and hypolimnetic layers. Nitrate + nitrite concentrations were low during December (26-38 ppb), but increased to approximately 90 ppb by March. However, soon after ice-out the nitrate + nitrite levels decreased sharply to reach extremely low levels in August (<0.5 ppb). In September, the nitrate + nitrite levels remained extremely low. Thus, total inorganic nitrogen levels decreased in the lake from a high of nearly 100 ppb during March to a low of approximately 6 ppb by September.

Reactive phosphorus levels underwent a seasonal change similar to that of the inorganic nitrogen levels (Table 8). For example, during the March sampling period reactive phosphorus levels were approximately 8 ppb, but by late June had decreased to below 4 ppb and by the end of September were further reduced reaching 2 ppb. However, reactive phosphorus was detectable throughout the sampling period compared to undetectable nitrate + nitrite levels, and only background levels of ammonium.

Total phosphorus levels peaked within the epilimnion after ice-out during June at 18 ppb (Table 8), and within the hypolimnion at 14 ppb during the same sampling date. In general, total phosphorus levels were in excess of 10 ppb throughout the study period and centered around 11 ppb. As such, the estimated yearly loading of phosphorus exceeds that of oligotrophic systems by 80% or was nearly double critical loading (Vollenweider, 1976).

Algal Biomass

Chlorophyll *a* (chl *a*) levels in Monsoon Lake were extremely low during the ice-over period of (December and March) reaching a maximum of 0.55 ppb in March (Table 8). After ice-out, chl *a* levels increased dramatically to 2.96 ppb by the end of June. This level of chl *a* persisted throughout the sampling period resulting in a summer average chl *a* content within the surface stratum of 3.08 ppb.

Table 8. Nutrient concentrations and algal pigments found within the epilimnion (1 m) and hypolimnion (12 m) of Monsoon Lake, 1981-82.

	Depth	Date 12/10/81	3/13/82	6/27/82	8/18/82	9/29/82
Total Phosphorus ($\mu g\ L^{-1}$ as P)	1 m	9.9	11.2	18.4	10.4	10.6
	12 m	13.3	11.6	14.4	11.7	11.9
Total Filterable Phosphorus ($\mu g\ L^{-1}$ as P)	1 m	9.9	9.8	7.4	6.0	4.6
	12 m	10.0	10.3	6.7	6.1	4.9
Filterable Reactive Phosphours ($\mu g\ L^{-1}$ as P)	1 m	6.6	7.7	3.1	2.8	2.2
	12 m	5.9	8.4	3.7	2.9	1.7
Nitrate + Nitrite ($\mu g\ L^{-1}$ as N)	1 m	26	89	2	<0.5	2
	12 m	38	90	21	8	4
Ammonium ($\mu g\ L^{-1}$ as N)	1 m	33	7	5	5	3
	12 m	23	8	11	4	2
Reactive Silicon ($\mu g\ L^{-1}$ as Si)	1 m	5520	5637	4228	4351	3638
	12 m	5274	5557	4489	855	3784
Iron ($\mu g\ L^{-1}$ as Fe)	1 m	26	10	139	53	17
	12 m	69	9	108	66	12
Algal pigments:						
Chlorophyll a ($\mu g\ L^{-1}$)	1 m	0.53	0.55	2.96	3.33	2.96
Phaeophytin ($\mu g\ L^{-1}$)	1 m	0.46	0.06	<U.D.*	0.50	<U.D.*

*Less than the detection limit.

Zooplankton

The zooplankton community consisted of seven species of macro-zooplankters, three cladocerans and four copepods in addition to three genera of rotifers (Table 9). The rotifers were represented by *Kellicottia longispina*, *Conchilus* sp. and *Conochiloides* sp.. The cladocerans were represented by *Bosmina longirostris*, *Daphnia middendorffiana*, and by the rare *Daphnia longiremis*. The copepod community consisted of *Cyclops columbianus*, *Cyclops vernalis* (extremely rare), *Diaptomus pribilofensis*, and *Heterocope septentrionalis*.

Within the zooplankton community, the rotifers were numerically dominant during both the spring (June) and late fall (September) samples i.e., either just after or during lake overturn, respectively. The density of *Conochiloides* ranged from none to 502,802 organisms/m^2, that of *Kellicottia longispina* ranged from 1,473 organisms/m^2 to 104,498 organisms/m^2, and finally the density of *Conochilus* ranged between none and 1,831 individuals/m^2.

Of the macro-zooplankton the numerically dominant organism was the cyclopoid copepod, *Cyclops columbianus* (along with a rare *Cyclops vernalis*) which ranged in density from 21,775 individuals/m^2 in mid-winter to 158,329 individuals/m^2 by late June. After *Cyclops*, the most abundant zooplankters were the calanoid copepods *Diaptomus* and *Heterocope*. The density of the herbivorous *Diaptomus* ranged from none in mid-winter to 55,732 organisms/m^2 in mid-August, and that of the predaceous *Heterocope* ranged from none in March to over 7,000/m^2 during June.

The other principle component of most pelagic macro-zooplankton communities, cladocerans, was noticably absent from the lake until the August and, in particular, the September samples. *Bosmina* densities ranged from none during March to a high of 1,035 individuals/m^2 during August, and, *Daphnia middendorffiana* was equally rare ranging in density from none to 1,035 individuals/m^2 in September. In essence, the filter feeding herbivorous macro-zooplankton were non-existent, and were consequently replaced as a feeding group by the rotifers.

As a group the macro-zooplankters in Monsoon Lake all possessed large body-sizes (Table 10). For example, *Daphnia middendorffiana* was particularly large ranging from 1.36 mm to 1.98 mm, but was very rare. *Bosmina longirostris* was again fairly rare, but was extremely large ranging from 0.60 mm to 0.69 mm in body-size. Of the copepods, the invertebrate predator *Heterocope* was the largest zooplankter found in the lake ranging from 1.57 mm to 2.99 mm in body-size. Following *Heterocope* in body-size was *Diaptomus* which ranged from a low of 0.60 mm (as just mature adults) in June to 1.32 mm in September. Finally, the smallest of the copepods was *Cyclops columbianus* which ranged in body-size from 0.66 mm in December to 0.90 mm in August and September.

Table 9. Numerical composition of the zooplankton community at Monsoon Lake, 1981-82.

Organism	Number/m^2 Date 12/10/81	3/13/82	6/30/82	8/18/82	9/29/82
Cladocera					
Bosmina longirostris	119	0	Rare	1,035	797
Daphnia middendorffiana	16	0	Rare	Rare	1,035*
Copepoda					
*Cyclops columbianus***	21,775	50,836	158,329	106,688	33,201
Diaptomus pribilofensis	0	517	17,829	55,732	29,458
Heterocope septentrionalis	79	0	7,131	366	797
Rotifera					
Kellicottia longispina	1,473	1,831	104,498	19,665	6,609
Conochilus sp.	517	0	0	0	1,831
Conochiloides sp.	0	1,074	502,802	2,388	94,745

**Daphnia longiremis* forma *typica* (rare).
***Cyclops vernalis* (rare).

Table 10. Mean body-size [mm $\pm$ 1 standard deviation (S.D.)] and sample size (n) of the macro-zooplankton from Monsoon Lake, 1981-82.

Taxa	12/10/81 n	12/10/81 $\bar{X} \pm$ S.D.	3/13/82 n	3/13/82 $\bar{X} \pm$ S.D.	6/30/82 n	6/30/82 $\bar{X} \pm$ S.D.	8/18/82 n	8/18/82 $\bar{X} \pm$ S.D.	9/29/82 n	9/29/82 $\bar{X} \pm$ S.D.
Copepoda										
Cyclops	30	0.66±.31	30	0.81±.21	30	0.81±.21	20	0.90±.06	20	0.90±.14
Diaptomus	1	1.19 --	3	0.96±.01	15	0.60±.09	20	1.26±.16	20	1.32±.09
Heterocope	4	2.90±.17	--	-- --	20	1.57±.31	7	2.72±.08	4	2.74±.11
Cladocera										
Daphnia	1	1.76 --	--	-- --	1	1.98 --	1	1.36 --	6	1.51±.37*
Bosmina	2	0.69±.01	--	-- --	5	0.60±.12	10	0.65±.10	10	0.67±.07

D. longiremus 0.90±.19 (n = 4).

Resident Fish

The only known resident fish species in Monsoon Lake is Arctic Grayling (*Thymallus arcticus*) with anadromous species such as sockeye salmon never having been observed in the lake.

DISCUSSION

Monsoon and Dickey lakes lie in the same general vicinity within the Gulkana River drainage, a tributary of the Copper River (Figure 1). Monsoon is one-tenth the size of Dickey Lake and is almost one-half as deep, but both are brown-water systems potentially accessable to anadromous salmonids. As such, both are potential sites for fish stock enhancement either by the technique of lake enrichment or by supplemental additions of rearing fry, i.e., lake stocking. Thus, our approach was designed to allow us to evaluate the relative potential of these alternative techniques.

The organic stain within both systems dictates to a large extent, the depth of the epilimnion and the depth of light penetration (Hasler et al. 1951). For both lake systems, the depth of the euphotic zone was less than or almost equal to the depth of the epilimnion, i.e., the entire trophogenic zone was well within the epilimnion. In addition, observed surface water temperatures never exceeded 15°C in either system. This is important in that water strata having temperatures above 15°C have been shown to be less efficient as a sockeye salmon rearing area (Goodlad et al. 1974). Finally, dissolved oxygen concentrations in both systems were consistently below 100% saturation even within the surface strata during the spring-summer period. However, lower oxygen concentrations are typical of brown water lakes (Johnson and Hasler, 1954), but extremely low oxygen levels were confined to strata (representing 1-3% of the total lake volume) immediately adjacent to the sediments.

Since the euphotic zone and the epilimnion were closely coupled, nutrient utilization within the trophogenic zone of both systems was fairly rapid following ice-out. This caused a decrease in inorganic nutrients within the epilimnion which was especially severe in regard to nitrogen levels within Dickey Lake (Table 11). In fact, the ratio of inorganic nitrogen to inorganic phosphorus (IN:IP) was unusally low ($\leqslant$6:1) in the lake throughout the year. However, the lowest ratios were found to occur in the upper portion of the epilimnion during June and August. These low ratios agree with finding a lack of silicon depletion within the epilimnion during the same time period. That is, low IN:IP ratios shift any competitive nutrient uptake advantage away from diatoms and toward green and blue-green species, i.e., those taxa which do not require silicon for growth. This same lack of silicon utilization was noted to occur in Monsoon Lake (Table 8) during the open water period as were relatively low IN:IP ratios which were $\leqslant$14:1. However, IN:IP ratios were consistently higher in Monsoon Lake when compared to the same sampling periods in Dickie Lake except during the fall overturn period. Because of the high nutrient ratios found to persist in the hypolimnion (12 m) of Monsoon Lake, a diatom bloom developed at the

Table 11. The ratio of inorganic nitrogen to inorganic phosphorus (by atoms) within the upper (1 m) and lower (8 m) strata of the epilimnion of Dickey Lake, and within the epilimnion (1 m) and hypolimnion (12 m) of Monsoon Lake.

Lake (Depth)	Date 12/10/81	3/15/82	6/30/82	8/18/82	9/29/82
Dickey (1 m)	5:1	6:1	<1:1	<1:1	6:1
Dickey (8 m)	5:1	6:1	1:1	1:1	6:1
Monsoon (1 m)	20:1	28:1	5:1	4:1	5:1
Monsoon (12 m)	23:1	26:1	20:1	10:1	4:1
Lake condition:	Ice-covered		Open water-stratified		Open water-isothermal

bottom of the thermocline during August. This bloom was responsible for the pulse in oxygen concentration (Figure 5), and the depletion of hypolimnitic silicon (Table 8). In contrast, bloom formation in the epilimnion was prevented by a low IN:IP ratio (4:1) which had already been established in the lake by the end of June.

Moreover, reactive phosphorus remained unutilized in both systems even during the open water period, and total phosphorus concentrations were extremely high for Alaska lakes. Thus, a nutrient enrichment program, if any, would be limited to pure nitrogen additions since both systems appear to be deficient in inorganic nitrogen. Similar additions have corrected similar nitrogen deficient conditions in Bear Lake, Alaska which has resulted in an almost two fold increase in coho salmon smolt production.

This is not to say that the present algal production found for either system was low, indeed, algal production (standing crop) was relatively high as chl a levels in Dickey Lake were greater than 8 ppb, and were greater than 3 ppb in Monsoon Lake (Tables 3 and 8). The importance of low nutrient ratios lies in the resultant composition of the algal community because, in general, green and blue green algal cells are less available as food to the zooplankton (Porter 1975, 1977). Zooplankton, being the basis for freshwater fish production for plantivorous fish, are the crucial link in the aquatic food chain between primary production and rearing of fry.

This potential reduction in algal quality caused by low nitrogen:high phosphorus loading from the bog, *Sphagnum* dominated watersheds [which are notoriously low in nitrogen (Wetzel 1975)] may reduce the importance of non-discriminating forms of filter feeding macro-zooplankton to the zooplankton community.

Indeed, the contribution of herbivorous filter feeding macro-zooplankton (e.g. *Daphnia* and *Bosmina*) to the zooplankton community of both lakes was extremely low (Tables 4 and 9). In contrast, the herbivorous rotifer population was relatively large as was the numerical density of the selective particle feeding *Diaptomus*. This suggests that herbivorous forms of zooplankton are not limited wholly by the quality of the algal community. In addition, the body-size of the zooplankters present in both systems are extremely large, further suggesting a lack of fish predation pressure (size selective) which would act to selectively remove the large body-sized cladocerans from the zooplankton community. Thus, we feel that the low density of *Bosmina* and *Daphnia* was not due to an insufficient food reserve or vertebrate predation pressure, but was caused by predation pressure from the invertebrate predator *Heterocope septentrionalis*. The calonoid copepod, *Heterocope septentrionalis*, is an extremely efficient predator on smaller body-sized species of zooplankton, particularly *Daphnia*, and *Bosmina* (O'Brien and Schmidt 1979, Luecke and O'Brien 1983).

The effect of invertebrate predation pressure on the zooplankton community structure is fundamentally different from that caused by vertebrate predation pressure. That is, rearing fish, being visual feeders detect

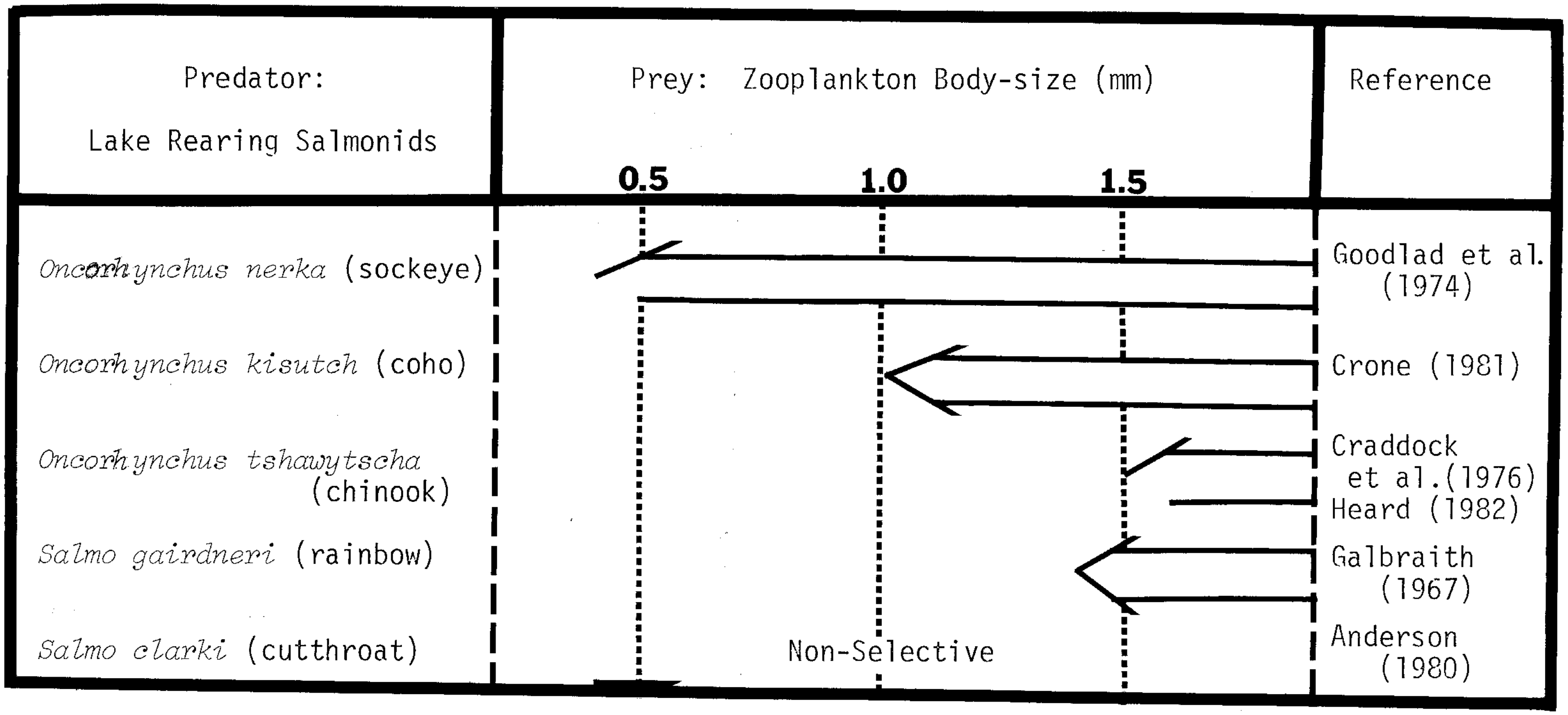


Figure 6. Generalized relationship between lake rearing salmonids during the first year of lake residence and the body-size of forage (zooplankton) capable of being retained in sufficient numbers to sustain efficient fry growth.

prey by visual size which in many instances is related directly to body-size. Actual selection of a given prey species is variable because of the differential escape abilities of the zooplankters, e.g., cladocerans are somewhat limited in escape ability relative to copepods (Drenner and McComas 1980). Thus, large cladocerans are usually the first prey to be eliminated by rearing fry. Increased protection from fish predation lies in the ability of the zooplankters to lower body-size, i.e., visual size. An observable result of such a strategy is that a given population of zooplankter, e.g., *Bosmina*, have been observed to have a mean body-size of 0.60 mm in a sockeye-poor lake versus a mean body-size of 0.38 mm in an adjacent sockeye-rich system (Koenings, unpublished data).

The response of the zooplankton community to invertebrate predation pressure is just the opposite to that described for vertebrate predation. Predaceous copepods are tactile feeders locating and holding prey by size, i.e., smaller and less robust organisms stand a greater chance of actually being consumed than do larger more robust organisms. Hence, protection from invertebrate predation lies in a large body-size. Thus, larger body-sized species of *Daphnia*, for example, would tend to have a survival advantage in invertebrate predator controlled systems, and smaller body-sized species would tend to have a survival advantage in a vertebrate predator controlled lake.

The dilemma facing herbivorous cladocerans is that lake systems contain both vertebrate and invertebrate predators. The response to this has been to increase tactile body-size without increasing visual body-size. Thus, within a species, e.g., *Daphnia longiremus*, two forms have been described (Riessen and O'Brien 1980) to be present under varying degrees of invertebrate predation pressure. One (described as *forma typica*) is present under conditions of less intense invertebrate predation pressure; the second (described as *forma cephala*) is present under conditions of significant invertebrate predation pressure. The *cephala* morph has an expanded transparent carapace which increases body-size discouraging invertebrate predation while at the same time maintaining a low visual body-size (O'Brien et al. 1980). Thus, the 'helmet' formation is analogous in function to the gelatinous sheath surrounding the cladoceran zooplankter, *Holopedium gibberum*.

The zooplankton community within both Monsoon and Dickey Lakes reflects predation pressure from two sources (vertebrate and invertebrate), but is defined to a greater extent by invertebrate predation pressure. Within Monsoon Lake, we feel that there was a signficant invertebrate pressure on the zooplankton community because of the presence of *Daphnia middendorffiana* (Table 9) a larger body-sized cladoceran (Table 10) compared to the rare (and more effectively preyed upon) *Daphnia longiremus* f. *typica*. In addition, vertebrate predation on the zooplankton is limited to Arctic grayling, a predator common to arctic and subarctic lakes. In contrast, Dickey Lake is populated by several vertebrate predators, i.e., Arctic grayling, lake trout, and the almost obligate planktivorous sockeye salmon fry. Sockeye fry are extremely efficient planktivores capable of retaining even extremely small body-sized zooplankton (Figure 6). Thus, in Dickey Lake, fish predation pressure may have removed the larger body-sized

Daphnia middendorffiana (Table 4) favoring the survival of the smaller body-sized *Daphnia longiremus* (Table 5). Yet, the invertebrate predation pressure was still present so, instead of the f. *typica* found in Monsoon Lake, the *Daphnia* in Dickey Lake were f. *cephala*. Finally, the body-sizes of *Cyclops, Bosmina*, and *Daphnia* were consistently larger in Monsoon Lake (which had relatively less vertebrate predation pressure) compared to Dickey Lake which sustained a relatively greater predation pressure by resident fish stocks. In contrast, the body-sizes of *Diaptomus* and *Heterocope* were consistently greater in Dickey Lake compared to those in Monsoon Lake. The differences between zooplankton body-sizes between the two lakes can be accounted for by the inability of *Cyclops, Bosmina*, and *Daphnia* to evade predation by both Arctic grayling and lake trout; whereas *Diaptomus* and *Heterocope* can more effectively avoid capture (Kettle and O'Brien 1978; Schmidt and O'Brien 1982).

Finally, if sufficient vertebrate predation pressure is placed on the zooplankton community of both lakes, *Heterocope septentrionalis* should be quickly eliminated from the lake as is the dipteran zooplankton predator *Chaoborus* following the introduction of planktivorous fish to previously fish-less systems (Van Ende 1975, Crone 1981). Following the elimination of *Heterocope, Bosmina* and *Daphnia* populations should increase, although the body-sizes will be smaller. In fact, *Daphnia middendorffiana* and *Daphnia longiremis* f. *cephala* should both disappear and be replaced by the smaller body-sized *Daphnia longiremus* f. *typica*. The importance of changing both the species composition of the zooplankton community and individual zooplankter body-sizes upon fish stock introduction lies in the differential foraging ability of the introduced fry (Figure 6). Thus, to take full advantage of the existing large body-sizes of the entire range of species within the zooplankton community of both lakes, fish stock introduction should begin with the fry requiring the largest forage items, i.e., rainbow trout and/or chinook salmon.

RECOMMENDATIONS

1) Fish stock introduction should proceed (if possible) with those species capable of retaining the larger forms of zooplankton already present in both systems.

2) A chinook/coho salmon introduction may well be suited for Monsoon Lake as it is a shallow system with a large littoral area providing both a pelagic and a benthic food source.

3) A rainbow trout introduction may well be suited for Dickey Lake as it has a larger pelagic area suitable for the planktivorous fry.

4) Sockeye salmon fry introductions are suitable for both systems with an anticipated combined capacity of from 3.0 to 3.5 million spring fry.

5) Nutrient enrichment may well increase the capacity of both systems to rear juvenile salmonids by the introduction of inorganic nitrogen, but may well be limited (benefit:cost wise) to the larger Dickey Lake system.

6) Continued monitoring of each system (or at a minimum of Dickey Lake) is desirable to document the shift in zooplankton species caused by the large scale introduction of a vertebrate predator, and to ascertain the effectiveness of the stocking at pre-determined fry densities.

ACKNOWLEDGEMENTS

The assistance of Dave Barto of the Prince William Sound Aquaculture Association in collecting a portion of the limnological samples is greatly appreciated. In addition, we gratefully acknowledge the assistance of Mike Scott, U. S. Bureau of Land Management in securing funds for this work under contract number AC950-CA2-1. Finally, the logistical support provided by Ken Roberson of the Alaska Department of Fish and Game was very much appreciated.

LITERATURE CITED

Anderson, S. R. 1980. Relationships between trout and invertebrate species as predators and the structure of the Crustacean and Rotiferan plankton in mountain lakes. pp 635-656. In: W. C. Kerfoot (ed.) Evolution and Ecology of Zooplankton Communities. University Press of New England. Hanover, New Hampshire. 793 p.

Brooks, J. L. 1957. The systemetics of North American *Daphnia*. Mem. Conn. Acad. Arts Sci. 13:1-180.

Craddock, D. R., Blahm, T. H. and W. D. Parente. 1976. Occurrence and utilization of zooplankton by juvenile chinook salmon in the lower Columbia River. Trans. Amer. Fish. Soc. 105:72-76.

Crone, R. A. 1981. Potential for production of coho salmon (*Oncorhynchus kitsutch*) in lakes with outlet barrier falls, Southeastern Alaska. Dissertation. University of Michigan, Ann Arbor, Michigan, USA.

Drenner, R. W. and S. R. McComas. 1980. The roles of zooplankton escape ability and fish size selectivity in the selective feeding and impact of planktivorous fish. pp. 587-593. In: W. C. Kerfoot (ed.) Evolution and Ecology of Zooplankton Communities. University Press of New England. Hanover, New Hampshire. 793 pp.

Edmondson, W. T., and G. G. Winberg (eds.). 1971. A manual for the assessment of secondary productivity in fresh waters. International Biological Program Handbook. 12:358 p.

Eisenreich, S. J., Bannerman, R. T., and D. E. Armstrong. 1975. A simplified phosphorus analysis technique. Environ. Letters 9:43-53.

Galbraith, M. G. 1976. Size-selective predation on *Daphnia* by rainbow trout and yellow perch. Trans. Amer. Fish. Soc. 96:1-10.

Goodlad, J. C., T. W. Gjernes and E. L. Brannon. 1974. Factors affecting sockeye salmon (*Oncorhynchus nerka*) growth in four lakes of the Fraser River system. J. Fish. Res. Board Can. 31:871-892.

Haney, J. F., and D. J. Hall. 1973. Sugar coated *Daphnia*: A preservation technique for cladocera. Limnol. Oceanogr. 18:331-333.

Harding, J. P., and W. A. Smith. 1974. A key to the British Freshwater cyclopid and calanoid copepods. Sci. Publ. Freshwater Biol. Assoc. 18:1-54.

Hasler, A. D., O. M. Brynildson, and W. T. Helm. 1951. Improving conditions for fish in brown-water bog lakes by alkalization. J. Wildlife Management. 15:347-352.

Heard, W. 1982. Personal communication. National Marine Fisheries Service, Auke Bay, Alaska.

Hutchinson, G. E. 1957. A Treatise on Limnology: Vol. I. Geography, Physics and Chemistry. John Wiley and Sons, N. Y. 1015 p.

Johnson, W. E. and A. D. Hasler. 1954. Rainbow trout production in dystrophic lakes. J. of Wildlife Management. 18:113-134.

Kettle, D., and W. J. O'Brien. 1978. Vulnerability of arctic zooplankton species to predation by small lake trout (*Salvelinus namaycush*). J. Fish. Res. Board Can. 35:1495-1500.

Koenings, J. P., Altland, B., Edmundson, J. Tobias, T., and D. Seagren. 1980. Alaska Department of Fish and Game Limnology Field and Laboratory Manual. (In review).

Luecke, C. and W. J. O'Brien. 1983. The effect of *Heterocope* predation on zooplankton communities in arctic ponds. Limnol. Oceanogr. 28:367-377.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

O'Brien, W. J., and D. Schmidt. 1979. Arctic *Bosmina* morphology and copepod predations. Limnol. Oceanogr. 24:564-568.

O'Brien, J. W., Kettle, Riessen, H., Schmidt, D. and D. Wright. 1980. Dimorphic *Daphnia longiremus*: Predation and competitive interactions between the two morphs. pp. 497-505. In: W. C. Kerfoot (ed.) Evolution and Ecology of zooplankton communites. University Press of New England. Hanover, New Hampshire. 793 pp.

Pennak, R. W. 1978. Fresh-water invertebrates of the United States, 2nd edition. John Wiley and Sons, New York. 803 p.

Porter, K. G. 1975. Viable gut passage of gelatinous green algae ingested by *Daphnia*. Verh. Internat. Verein. Limnol. 19:2840-2850.

Porter, K. G. 1977. The plant-animal interface in freshwater ecosystems. Amer. Sci. 65:159-170.

Reimann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. Limnol. Oceanogr. 23:1059-1066.

Riessen, H. P. and W. J. O'Brien. 1980. Re-evaluation of the taxonomy of *Daphnia longiremus* Sars, 0862 (Cladocera): Description of a new morph from Alaska. Crustaeana 38:1-11.

Roberson, K. 1982. Alaska Department of Fish and Game, Commercial Fisheries Division, Glennallen.

Schmidt, D. and W. J. O'Brien. 1982. Planktivorous feeding ecology of Arctic grayling (*Thymallus arcticus*). Can. J. Fish. Aquat. Sci. 39:475-482.

Stainton, M. P., M. J. Capel, and F. A. J. Armstrong. 1977. The chemical analysis of freshwater, 2nd ed. Fish Mar. Serv. Misc. Spec. Publ. 25:1-166.

Strickland, J. D. H., and T. R. Parsons. 1972. A practical handbook of seawater analysis, 2nd ed. Fisheries Research Board of Canada Bulletin. 167:310 p.

Vollenweider, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrabiol. 33:53-83.

Wetzel, R. G. 1975. Limnology. W. B. Saunders, Co. 743 pp.

Wilson, M. S., and H. C. Yeatman. 1959. Free-living copepoda. pp. 735-861. In: W. T. Edmondson [ed.], Fresh-water biology, 2nd ed. John Wiley and Sons, Inc. 1248 p.

Von Ende, C. N. 1975. Organization of bog lake zooplankton communities: Factors affecting the distribution of four *Chaoborus* species (Diptera Chaoboridae). Dissertation. University of Notre Dame, Notre Dame, Indiana, USA.